

# Probing dark matter crests with white dwarfs and IMBHs

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## ABSTRACT

White dwarfs (WDs) are the most promising captors of dark matter (DM) particles in the crests that are expected to build up in the cores of dense stellar clusters. The DM particles could reach sufficient densities in WD cores to liberate energy through self-annihilation. The extinction associated with our Galactic Centre, the most promising region where to look for such effects, makes it impossible to detect the potential associated luminosity of the DM-burning WDs because due to distance and extreme extinction the apparent near-infrared magnitudes of the WDs would be fainter than about 30 mag. However, in smaller stellar systems which are close enough to us and not heavily extincted, such as  $\omega$ -Cen, we may be able to detect DM-burning WDs. In this work we investigate the prospects of detection of DM-burning WDs in a stellar cluster harbouring an intermediate-mass black hole (IMBH), which leads to higher densities of DM at the centre as compared with clusters without one. We calculate the capture rate of WIMPs by a WD around an IMBH and estimate the luminosity that a WD would emit depending on its distance to the center of the cluster. Direct-summation  $N$ -body simulations of  $\omega$ -Cen yield a non-negligible number of WDs in the range of radii of interest. We apply our assumption to published HST/ACS observations of stars in the center of  $\omega$ -Cen to search for DM burning WDs and, although we are not able to identify any evident candidate because of crowding and incompleteness, we prove that their bunching up at high luminosities would be unique. We predict that DM burning will lead to a truncation of the cooling sequence at the faint end. The detection of DM burning in future observations of dense stellar clusters, such as globular clusters or ultra-compact dwarf galaxies could allow us to probe different models of DM distributions and characteristics such as the DM particle scattering cross section on nucleons. On the other hand, if DM-burning WDs really exist, their number and properties could give hints to the existence of IMBHs.

**Key words:** globular clusters: individual:  $\omega$ -Cen, white dwarfs, dark matter, black hole physics

## 1 INTRODUCTION

Weakly interacting massive particles (WIMPs) form high density cusps in dense stellar systems, as seen with collisionless cosmological  $N$ -body simulations (Navarro et al. 1997; Moore et al. 1999). More recent simulations have derived the result that this is particularly true in the gravitational well of massive black holes (henceforth MBHs; see Gondolo & Silk 1999; Gnedin & Primack 2004a; Bertone & Merritt 2005). Within a certain radius of the MBH any member of the stellar distribution has a big WIMP capture rate. The successive annihilation of these particles in

the core of the stars releases a significant amount of energy and hence impinges their evolution and appearance (Salati & Silk 1989; Bouquet & Salati 1989; Moskalenko & Wai 2007; Scott et al. 2009; Casanellas & Lopes 2009). In the case of main-sequence stars, the first two references describe the potential suppression of stellar core convection in these stars, so that there could be an agglomeration of stars in our Galactic Center concealing their spectral type and being interpreted as cold red giants. Moskalenko & Wai (2007) found that the WIMP capture rate and annihilation is remarkably large for WDs. They derived luminosities from the WIMP annihilation only that are comparable to or even larger than the standard thermal luminosity of WDs, of the order  $L_{\text{WD}} \sim 3 \times 10^{34} \text{ erg s}^{-1} \sim 10 L_{\odot}$ , with  $L_{\odot}$  the luminos-

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ity of the sun. In this respect, WDs are the most promising candidates to probe DM agglomeration zones, such as our galactic nucleus or the center of dwarf spheroidal galaxies and globular clusters (Bertone & Fairbairn 2008; Hooper et al. 2010; McCullough & Fairbairn 2010; Fan et al. 2011; Hurst et al. 2015).

This article is organised as follows: In section 2 we calculate the distribution of DM particles around a massive black hole such as the one that might be lurking in  $\omega$ -Cen. Later, in section 3 we estimate the capture rates and, accordingly, the luminosities emitted by WDs of different masses and compositions. In section 4 we model the distribution of WDs as a function of radius in a cluster harbouring a massive black hole. We discuss observational predictions and compare them with existing photometric data in section 5. Finally, we summarise and conclude the most important implications of our analysis in section 6.

## 2 DARK MATTER DENSITY PROFILE AT $\omega$ -CEN

Although it is not possible to precisely determine the quantity of dark matter (DM) present in globular clusters, we can estimate the DM density profile in  $\omega$ -Cen based on current observations and simulations. These clusters are thought to have formed in the center of DM subhaloes in the early Universe, thus being born as strongly DM dominated objects (Peebles 1984). However, in the scenario of hierarchical structure formation, clusters were captured by galaxies, losing most of their extra-nuclear mass due to tidal stripping, but still retaining large quantities of DM concentrated in their cores, as indicated by the results of numerical simulations (Tsuchiya et al. 2003; Mashchenko & Sills 2005; Ibata et al. 2013).

It is important to note that  $\omega$ -Cen may not be a normal globular cluster. It is considered rather likely that it is the stripped nuclear cluster of a tidally accreted galaxy which, reinforced by its far more complex stellar population, compared to normal clusters. The fact that  $\omega$ -Cen may be a nuclear star cluster remnant is also used to argue that it may have an IMBH at its center (see e.g. the introduction of van der Marel & Anderson 2010).

In the case of  $\omega$ -Cen, with a cluster mass of  $2.5 \times 10^6 M_\odot$  (van de Ven et al. 2006), we can estimate the initial mass of the DM subhalo to be  $5 \times 10^8 M_\odot$  ( $M_{DM,0} \approx 0.0038^{-1} M_{GC}$ , with  $M_{GC}$  the mass of the globular cluster, see Griffen et al. 2010), and its present value to be  $10^7 M_\odot$  ( $M_{DM} \approx 0.02 M_{DM,0}$ , see Gao et al. 2004). The density of the initial DM halo in  $\omega$ -Cen was modelled assuming a NFW profile (Navarro et al. 1996):

$$\rho_{\chi,\text{NFW}}(r) = \frac{\rho_c}{(r/r_s)(1+r/r_s)^2}, \quad (1)$$

with  $r_s = 685$  pc and  $\rho_c = 0.07 M_\odot/\text{pc}^3$ . This parametrization of  $\rho_\chi$  correctly reproduces the results of DM N-body simulations, and predicts a  $\rho \propto r^{-1}$  cusp in the centre of the DM halo. Other parametrizations would imply either steeper profiles (Moore et al. 1998) or cored profiles (Burkert 1996), so this uncertainty should be taken into account when interpreting our results.

It has been shown that the inclusion of the baryonic feedback leads to an adiabatic contraction of the DM halo (Blumenthal et al. 1986). This mechanism was implemented using the baryonic mass profile observed in  $\omega$ -Cen (Noyola et al. 2008), following the procedure described in Gnedin et al. (2004), leading to a contracted profile  $\rho_{\chi,\text{NFW-AC}}(r)$ . Furthermore, the DM cusp created by the adiabatic contraction is shallowed by the heating of the DM particles due to the collisions with the stars (Merritt 2004), creating a core of constant density up to  $r_{\text{DMh}}$ , the radius at which the two-body relaxation time defined by the stars,  $T_r(r)$ , becomes greater than the age of the cluster. In  $\omega$ -Cen the  $r_{\text{DMh}}$  was found to be of approximately 3.5 pc (van de Ven et al. 2006).

In the case of DM haloes with a central MBH, the central cusp in the stellar density leads to an overdensity in the inner region of the final DM profile, the so-called *crest*, as shown by Fokker-Planck and direct  $N$ -body integrations (Gnedin & Primack 2004b; Merritt et al. 2007).

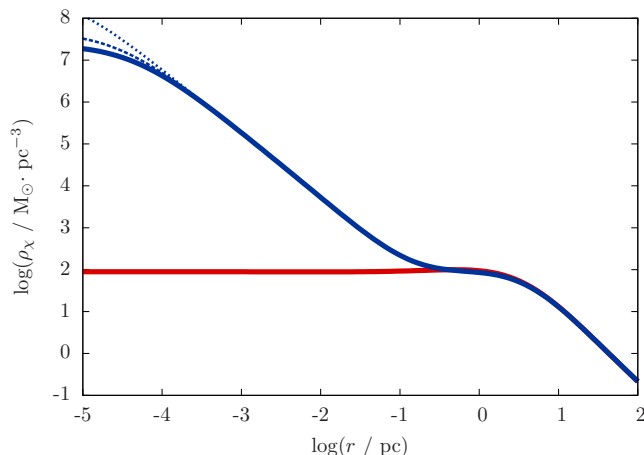
The characteristic time for the growth of a stellar cusp and a DM crest is approximately  $0.5 T_r(r_h)$ , where  $r_h$  is the gravitational influence radius of the central MBH. After this time, the stars around the MBH form a Bahcall-Wolf cusp:  $\rho_\star(r) \propto r^{7/4}$  (see e.g. Peebles 1972; Bahcall & Wolf 1976; Amaro-Seoane et al. 2004), triggering the formation of a DM crest with a density profile  $\rho_\chi \propto r^{-1.5}$ . In  $\omega$ -Cen there is no clear *observed* evidence for the cusp, probably due to the incompleteness of the star counts in the centre (crowding, see section 5 on the limitations of the observations). In this work we assume the existence of the cusp, as expected theoretically in the works we just mentioned.

Thus, the presence of an IMBH in the centre of  $\omega$ -Cen strongly impacts the estimation of the DM distribution around it. However, the observational evidence for its existence remains controversial. Noyola et al. (2010) found evidence for an IMBH, but this is contested by van der Marel & Anderson (2010). Key problems are the low angular resolution used in previous spectroscopic work on the kinematics of stars and the determination of the location of the center of the cluster. Consequently, here we will consider the DM distribution in both scenarios, with and without an IMBH in the center of  $\omega$ -Cen (van der Marel & Anderson 2010; Noyola et al. 2010).

Assuming a central IMBH of mass  $M_\bullet \approx 10^4 M_\odot$ ,  $r_h$  was found to be equal to 0.12 pc (taking an heliocentric distance to  $\omega$ -Cen of 4.8 kpc, so  $r_h \sim 5'' \sim 0.12$  pc Jalali et al. 2012) and  $0.5 T_r(r_h) \sim 10^9$  yr (van de Ven et al. 2006), well below the age of the  $\omega$ -Cen. In this case, the final DM density profile of  $\omega$ -Cen was estimated to be:

$$\rho_{\chi,\bullet}(r) = \begin{cases} \rho_{\chi,\text{core}} \times (r/r_h)^{-1.5}, & r < r_h, \\ \rho_{\chi,\text{core}} \equiv \rho_{\chi,\text{NFW-AC}}(r_{\text{DMh}}), & r_h \leq r \leq r_{\text{DMh}}, \\ \rho_{\chi,\text{NFW-AC}}(r), & r > r_{\text{DMh}}, \end{cases} \quad (2)$$

similar to what has been estimated in the literature for other clusters harbouring IMBHs (Abramowski et al. 2011; Feng et al. 2012). Finally, we also consider an upper limit to the DM density due to the DM annihilations,  $\rho_{\text{ann}} \approx m_\chi / \langle \sigma_a v \rangle t_{\text{GC}}$ , where  $m_\chi$  is the WIMP mass,  $\langle \sigma_a v \rangle$  its thermally averaged annihilation cross section, and  $t_{\text{GC}}$  the time since the formation of the crest, which we conservatively assumed to be the age of  $\omega$ -Cen. This limit is approximately



**Figure 1.** Density profile of the DM halo in  $\omega$ -Cen. The red line shows  $\rho_\chi(r)$  as if there was no IMBH in the center of the cluster, while the blue lines show  $\rho_{\chi,\bullet}(r)$  for a IMBH of  $M_\bullet \approx 10^4 M_\odot$  for  $m_\chi = 5$  GeV (continuous), 10 GeV (dashed) and 100 GeV (dotted).

equal to  $2 \times 10^7$ ,  $4 \times 10^7$  and  $4 \times 10^8 M_\odot/\text{pc}^3$  for WIMP masses of 5, 10 and 100 GeV. These limits only flatten the DM density profile at distances below  $10^{-3}$  pc.

In the scenario where  $\omega$ -Cen harbours no IMBH, the DM distribution would remain cored in the center, leading to the following DM density profile:

$$\rho_\chi(r) = \begin{cases} \rho_{\chi,\text{core}} \equiv \rho_{\chi,\text{NFW-AC}}(r_{\text{DMh}}), & r < r_{\text{DMh}}, \\ \rho_{\chi,\text{NFW-AC}}(r), & r \geq r_{\text{DMh}}, \end{cases} \quad (3)$$

Both DM density profiles are shown in Figure 1.

### 3 DARK MATTER CUSPS AND IMBHs

In order to calculate the number of WIMPs captured by the WD, we have to calculate the capture rate  $\mathcal{C}$  of a WD of mass  $M_*$  for a Maxwellian WIMP velocity distribution. We assume the WD moving at a velocity  $v_*$  relative to the observer, so that the capture rate is (Gould 1987),

$$\mathcal{C} = 4\pi \int_0^{R_*} dr r^2 \frac{dC(r)}{dV}, \quad (4)$$

where  $dC(r)/dV$  can be calculated with the expressions of the same work. The total capture rate depends mainly on the density of DM around the star, the density and composition of the WD, and the spin-independent scattering cross-section of the DM particles off nucleons,  $\sigma_\chi$ . As noted by Moskalenko & Wai (2007), WD are the most promising captors of WIMPs due to the fact that the cross section is proportional to  $A_n^4$ , with  $A_n$  the atomic number of the principal element of which the WD's nucleus is composed. The maximum interaction cross-section  $\sigma_{\text{max}}$  is given by the geometrical limit  $\pi R_*^2$ , with  $R_*$  the radius of the star, and can be calculated as

$$\sigma_{\text{max}} A_n^4 \frac{M_*}{M_n} = \min(\sigma_\chi A_n^4 \frac{M_*}{M_n}, \pi R_*^2), \quad (5)$$

where  $M_n$  is the nucleus mass and  $\sigma_\chi$  the cross section of the particle. This leads to limits on our cross section to values

around  $\sigma_{\text{max}} = 10^{-42} \text{ cm}^2$ , depending on the composition of the WD and its mass.

We take the values of the distribution of  $\rho_\chi$  obtained in section 2 to estimate the capture rates. The capture rate  $\mathcal{C}$  can be easily converted into luminosities by using  $L_\chi = \mathcal{C} m_\chi$  (Salati & Silk 1989). The luminosities due to DM annihilations for models of WDs with different compositions, masses and radius are shown in Table 1. The principal factor in the luminosity, and the related effective temperature,  $T_{\text{eff}}$ , is the radius of the star, followed by the atomic number. Oxygen WDs have the largest values, followed by Carbon WDs and the lowest values are for Helium WDs. We display the value of the luminosity due to the burning of DM at three particular radii taken from the centre of the cluster, assumed to be located at the position of the IMBH: 2.5, 0.1 and 0.01 pc. While the DM density achieves higher values at shorter radii, we choose 0.01 pc as our lowest value, because shorter radii will contain very small numbers of WDs, thus making any observational/statistical test inconclusive. In the table we depict the associated luminosities for the different kinds of WDs at different radii. For all the cases studied here,  $L_\chi$  does not depend on the mass of the DM particle  $m_\chi$  (because  $\mathcal{C} \propto m_\chi^{-1}$  in this regime).

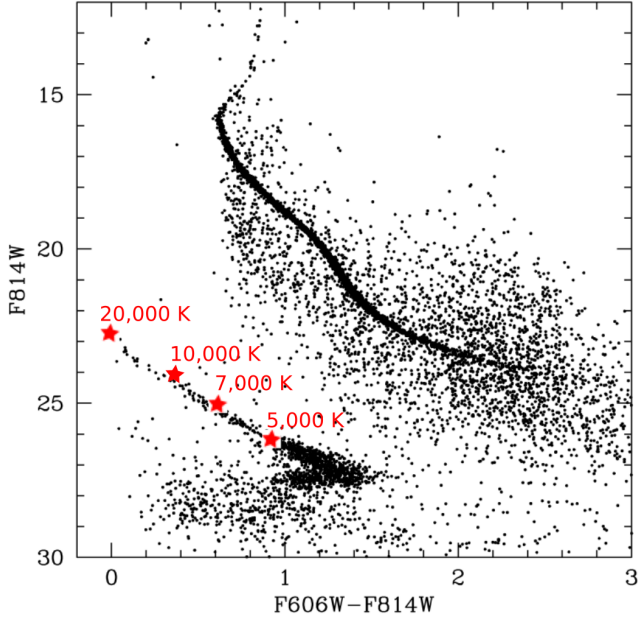
We note that  $m_\chi$  should be below 6 GeV to avoid the current limits from direct detection experiments on the spin-independent DM-nucleon cross sections (Akerib et al. 2014). However, given the present controversy between contradictory positive and null results in different experiments, it is worth to explore the DM parameter space more broadly. In particular, for  $m_\chi \approx 10$  GeV, our results show how WDs would be lightened up if DM has the properties to explain the recent positive results in some DM detectors (Bernabei et al. 2008; Angloher et al. 2012; Agnese et al. 2013).

### 4 DISTRIBUTION OF WHITE DWARFS IN $\omega$ -CEN

An obvious question to address is that of the number of WDs available in the range of radii of interest.  $\omega$ -Cen is a very massive globular cluster, or a nuclear cluster remnant. Since we are interested in an accurate distribution of stars along the radius, we use the results of a direct-summation  $N$ -body integration to model this.

We employ the simulation data of McNamara et al. (2012) with a 1% MBH in mass. We note that these simulations were for NGC 6266, but have been adapted to fit the profile of  $\omega$ -Cen. Ideally one would model the whole cluster with a direct-summation integrator but the number of stars and the long integration time makes it impossible. The simulation uses 1,580,430 stars, which is below the expected number of stars for  $\omega$ -Cen (about 1/6 of the total number), but representative and the relative distribution is correct, in the sense that that model has the same half-mass radius as  $\omega$ -Cen. It hence represents a fair lower-limit for the total number of WDs distributed along the radius for a cluster as massive as  $\omega$ -Cen.

In the simulation we have three different mass groups: light WDs, of masses  $< 0.6 M_\odot$ , medium ones, with masses larger than  $0.6 M_\odot$  but less than  $0.8 M_\odot$ , and heavy ones, with masses  $\leq 0.8 M_\odot$ . For small radii, up to 0.01 pc, we find in the simulation that there are 1 light WD, 0 medium



**Figure 2.** CMD of a deep HST/ACS observation of a field in the globular cluster NGC 6397 (Hansen et al. 2007). The red stars and labels refer to blackbody models of white dwarfs with effective temperatures of 5000, 7000, 10000, and 20000 K.

ones, and 43 heavy ones. Between 0 and 0.5 pc we have 154 light WDs, 77 medium WDs and 95 heavy ones. Out to 1 pc there are 726 light WDs, 255 medium ones and 189 heavy WDs. Up to 10 pc, 25378 light WDs, 4959 medium ones, and 1864 heavy WDs. We therefore find that the number of WDs at the radii of interest is non-negligible.

## 5 OBSERVATIONAL IMPLICATIONS

What could be the observational signatures of DM burning in WDs in a globular cluster? In Fig. 2 we show a deep colour-magnitude diagram (CMD) of a field in a globular cluster (Hansen et al. 2007). The WD cooling sequence appears to the bottom left, at significantly fainter magnitudes and bluer colours than the main sequence. The data are deep enough to reach all the way to the bottom of the WD cooling sequence, which is truncated at  $F814W \approx 27.6$  mag. We overplot the data points from four simple blackbody WD models over the data in the figure. As can be seen, the blackbody approximation works well for most of the cooling sequence, but at the coolest temperatures/faintest magnitudes, the cooling sequence turns toward bluer colours and deviates from what we would expect from simple blackbody cooling.

Panei et al. (2000) calculated the mass-radius relationship for white dwarfs of different core compositions with the most common envelopes (hydrogen and helium) for a range of temperatures. We take  $0.46 M_{\odot}$  stars with He cores and  $0.55 M_{\odot}$  stars with C and O cores, since these were shown to be most common in  $\omega$ -Cen by Bellini et al. (2013). Using these values, we then compute the luminosity from DM annihilation inside the WDs at different radial distances from the center of the  $\omega$ -Cen cluster, as explained in Sections 2 and 3. The results for different WD models and distances to

the center of  $\omega$ -Cen are shown in Table 1. We then add this luminosity to the luminosity of a WD that is not burning DM particles. Subsequently we calculate the total effective temperature of the WD while it is burning DM. Adding the effect of DM results simply in an increased  $T_{\text{eff}}$ . Observationally, this corresponds to the WD moving along the cooling sequence towards brighter magnitudes and bluer colours in a CMD. In particular, DM burning will impose a lower limit on the effective temperature of WDs, even if they are very old and had time to cool for almost a Hubble Time. Hence, we predict that DM burning will lead to a truncation of the cooling sequence at the faint end.

To facilitate the following considerations, we note that, according to Table 1, the predicted DM luminosities of WDs differ by  $\lesssim 10\%$  for different WD compositions and temperatures and depend primarily on their distance from the cluster centre and on the presence of a central IMBH or not. Hence, we limit our computations to three cases: (1) DM burning within the cluster core and absence of an IMBH, (2) DM burning within the cluster core with an IMBH at a distance of 0.1 pc from the latter, and (3) as (2) but at a distance of 0.01 pc from the IMBH. From Table 1 we obtain for these cases mean DM luminosities of (1)  $5.0 \times 10^{-4}$ ,  $1.0 \times 10^{-3}$ , and  $2.6 \times 10^{-2}$  solar luminosities. We use a single mean radius of 0.015 solar radii for all WD models. We approximate the spectral energy distributions (SEDs) of the WDs by blackbodies. In the blackbody-approximation, the luminosity/SED of the WDs is determined simply by their radius and effective temperature. The relation between these quantities and the effective temperature is given by the Stefan-Boltzmann law:

$$L = 4\pi R^2 \sigma T_{\text{eff}}^4, \quad (6)$$

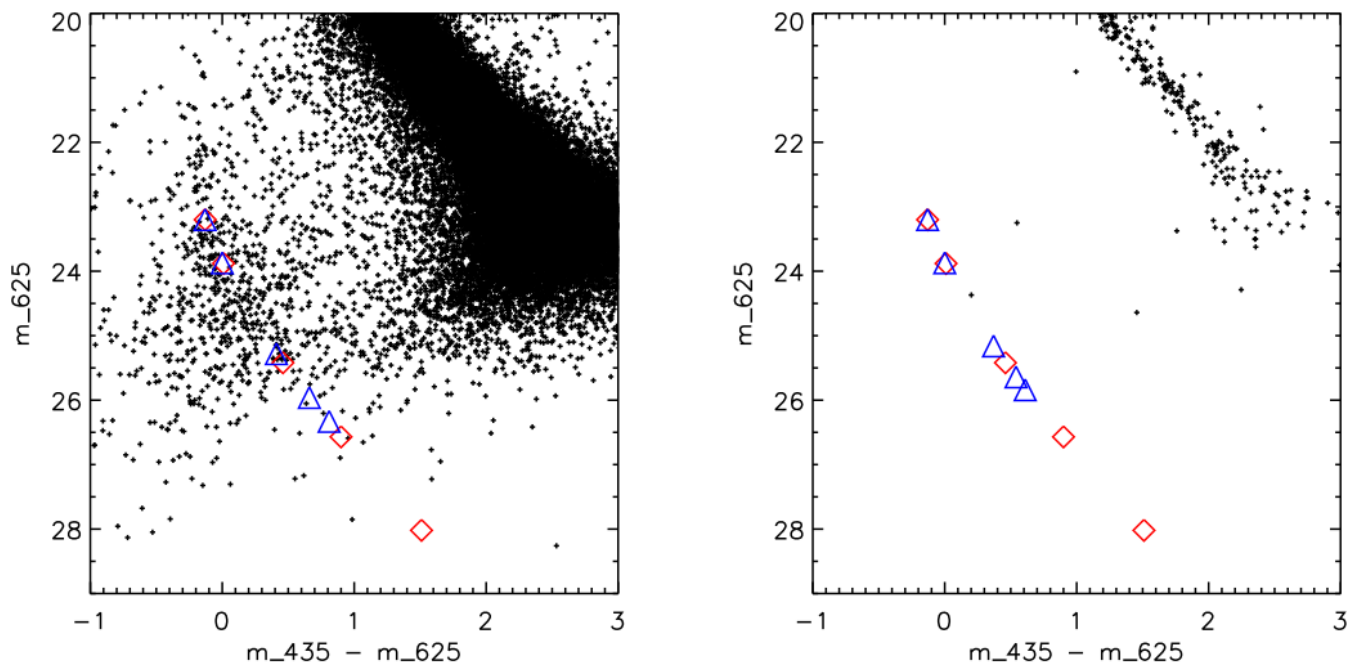
where  $L$  is the WD's luminosity,  $R$  its radius,  $T_{\text{eff}}$  its effective temperature, and  $\sigma \approx 5.6704 \times 10^{-8} \text{ J s}^{-1} \text{ m}^{-2} \text{ K}^{-4}$ .

For the properties and distribution of DM and stars in  $\omega$ -Cen that we assume in this paper, we obtain minimum effective Temperatures of  $T_{\text{eff}} \approx 7,000$  K for WDs inside the core, i.e. within 2.5 pc of the centre of  $\omega$ -Cen. If there exists an IMBH, then we obtain minimum values of  $T_{\text{eff}} \approx 8,500$  K for WDs within 0.1 pc and of  $T_{\text{eff}} \approx 19,000$  K for WDs within 0.01 pc of the black hole, inside the DM cusp.

In order to consider the observability of DM burning WDs we use HST ACS F435W and F625W photometry of stars in  $\omega$ -Cen by Anderson & van der Marel (2010). We show the CMDs for regions within 2.5 pc and 0.1 pc projected distance from the centre of the cluster as adopted by Anderson & van der Marel (2010) in Fig. 3. We indicate the positions of WDs with different effective temperatures in these CMDs, as well as how they would be changed through DM burning. According to our assumptions, the WD cooling sequence should be truncated near  $T_{\text{eff}} = 7500$  K in the cluster core, independent of the presence of an IMBH. If there is an IMBH, then the cooling sequence would appear truncated around  $T_{\text{eff}} = 8700$  K for distances  $< 0.1$  pc from the centre. Here, for the simplicity of argument, we neglect any projection effects. The latter would result in some lower temperature WDs from larger three-dimensional distances to appear below the truncation temperatures in the CMDs. We will not go through a detailed analysis of projection effects here because we are mainly interested in a zero order description of the potential effects of DM burning in WDs.

**Table 1.** Characteristics of the WD models, including their standard luminosities and the luminosities due to DM burning in the scenarios without an IMBH at the center of  $\omega$ -Cen ( $L_{\chi, \text{No BH}}$ , valid for  $r < 2.5$  pc) and with an IMBH ( $L_{\chi, \bullet}$ ) for WDs at distances of 2.5, 0.1 and 0.01 pc from it.

Element	Mass ( $M_{\odot}$ )	Radius ( $R_{\odot}$ )	Luminosity ( $L_{\odot}$ )	$T_{\text{eff}}$ (K)	$L_{\chi, \text{No BH}} = L_{\chi, \bullet}(r = 2.5 \text{ pc})$ ( $L_{\odot}$ )	$L_{\chi, \bullet}(r = 0.1 \text{ pc})$ ( $L_{\odot}$ )	$L_{\chi, \bullet}(r = 0.01 \text{ pc})$ ( $L_{\odot}$ )
He	0.46	0.0160	0.00475	12000	$4.79 \times 10^{-4}$	$9.78 \times 10^{-4}$	$2.47 \times 10^{-2}$
C	0.55	0.0149	0.162	30000	$5.35 \times 10^{-4}$	$1.09 \times 10^{-3}$	$2.76 \times 10^{-2}$
O	0.55	0.0155	0.324	35000	$5.55 \times 10^{-4}$	$1.13 \times 10^{-3}$	$2.87 \times 10^{-2}$
He	0.46	0.0152	0.000848	8000	$4.55 \times 10^{-4}$	$9.29 \times 10^{-4}$	$2.35 \times 10^{-2}$
C	0.55	0.0145	0.0735	25000	$5.19 \times 10^{-4}$	$1.06 \times 10^{-3}$	$2.68 \times 10^{-2}$
O	0.55	0.0147	0.141	30000	$5.26 \times 10^{-4}$	$1.07 \times 10^{-3}$	$2.72 \times 10^{-2}$
He	0.46	0.0143	0.0000469	4000	$4.28 \times 10^{-4}$	$8.74 \times 10^{-4}$	$2.21 \times 10^{-2}$
C	0.55	0.0141	0.0285	20000	$5.05 \times 10^{-4}$	$1.03 \times 10^{-3}$	$2.61 \times 10^{-2}$
O	0.55	0.0143	0.0716	25000	$5.12 \times 10^{-4}$	$1.05 \times 10^{-3}$	$2.64 \times 10^{-2}$



**Figure 3.** CMDs of the stars detected within a projected radius of 2.5 pc (left) and 0.1 pc (right) from the center of  $\omega$ -Cen (Anderson & van der Marel 2010), with blackbody WD models overplotted. Red diamonds correspond to WDs at  $T_{\text{eff}} = 30000, 20000, 10000, 7000$ , and  $5000$  K. Blue triangles correspond to blackbody models of the same WDs with increased luminosity through DM burning in the core, i.e. within 2.5 pc of the centre of the cluster (left:  $T_{\text{eff}, \text{DM}} = 30000, 20100, 10600, 8350$ , and  $7500$  K) and at 0.1 pc distance from a hypothetical central IMBH (right:  $T_{\text{eff}, \text{DM}} = 30050, 20150, 11100, 9300$ , and  $8700$  K).

The CMDs of  $\omega$ -Cen show an almost complete absence of WDs at  $T_{\text{eff}} \lesssim 10000$  K and within 0.1 pc of the centre. This is, however, merely an effect of incompleteness due to sensitivity and crowding. Not even the sensitive, high-angular resolution observations made possible by the HST can resolve the dense core of  $\omega$ -Cen sufficiently well to probe the WD cooling sequence with high completeness down to low temperatures. Figure 5 of Anderson & van der Marel (2010) indicates a completeness of only around 25% for stars of  $\text{mag}_{F435W} \approx 25$  within 0.35 pc of the cluster center. Hence, incompleteness hinders us from drawing any meaningful conclusion on WDs in the center of  $\omega$ -Cen. Crowding becomes less severe at greater distances, but the situation does not change much, since the projected surface density is rather flat in the core of  $\omega$ -Cen (Anderson & van der Marel

2010). The completeness for stars of  $\text{mag}_{F435W} \approx 25$  within 2.5 pc of the cluster center is still only about 35%. Therefore, although the CMD at the left panel of Fig. 3 may indicate a lack of WDs with  $T_{\text{eff}} \lesssim 8000$  K, this is not a reliable measurement. We also used other observations (Bellini et al. 2013), but the situation remains largely unchanged. With an estimated central density of  $5.6 \times 10^7 M_{\odot} \text{ pc}^{-3}$  (Noyola et al. 2008) the central regions of  $\omega$ -Cen cannot be resolved down to faint magnitudes with high completeness by any currently existing instrument.

The observational situation will not be much different for other globular clusters, at least the ones that are massive and dense enough to possibly hold an IMBH at their centres. A breakthrough can be expected with the advent of adaptive optics (AO) assisted imagers on the next gener-

ation of 30-40 m-class telescopes. The near-infrared imager planned for the 39m ESO E-ELT, MICADO, for example, will provide an angular resolution of 6-12 milli-arcseconds, depending on the observing wavelength. This will be almost five times better than what can be done with AO imagers on current 8m-class telescopes. Hence, confusion will be reduced by a factor of  $> 20$ . Along with the high point-source sensitivity of the E-ELT this should make it possible to resolve the cores of nearby globular clusters and probe the WD cooling sequences down to their bottom.

Hence, the truncation of the WD cooling sequence at the cool end in dense globular clusters can serve as a future observational test that will set constraints on the properties of WIMP DM and, in the globular cluster cores, on the mass of a potential IMBH. If DM does indeed change WD luminosities in the predicted way, then by comparing the statistical properties of WDs in the central  $\sim 0.01 - 0.1$  pc with their properties at distances of 1-2 pc may even provide a conclusive answer to the presence of an IMBH, independent of stellar dynamical measurements.

## 6 CONCLUSIONS

We show that clusters are favorable environments to search for the DM effects on stars and they could provide a tool to constrain the properties of DM. These clusters are the only environments where we will be able to clearly observe stars in an area rich in DM, unlike other obscured regions as the galactic center.

We found that DM burning in WDs would increase their effective temperature, resulting in their moving up the cooling sequence. In addition, we show that the minimum effective temperature of WDs due to DM burning strongly depends on the presence of an IMBH at the center of the globular cluster. It will not be possible to distinguish an individual DM burning WD from a normal one. However, we have predicted a statistical signal if DM is present, particularly since WDs cool faster at higher temperatures, meaning they should spend less time at the top of the cooling sequence. If DM burning takes place, we expect a clear lack of cool WDs near the cluster core and a distinct bunching of WDs at higher temperatures. Deep, high angular resolution imaging, such as it could be provided by a future 30-40m telescope will be needed to explore the lack of an IMBH in the center of  $\omega$ -Cen or, alternatively, it may prove that DM does not have the large scattering cross-section on nucleons required to produce these annihilation luminosities.

On the other hand, the observation of normal numbers of cool WDs in the centre of  $\omega$ -Cen would be in disagreement with  $\omega$ -Cen harbouring an IMBH and DM having the properties to explain the positive results in DAMA, CRESST and CDMS experiments. Unfortunately, conclusive observational tests appear to be currently out of reach. The CMD from present HST observations of  $\omega$ -Cen cannot provide any positive indication of DM burning due to the lack of completeness of the observations in the reduced volume in the core of  $\omega$ -Cen in which DM burning can be significant. The high angular resolution and sensitivity of future extremely large telescopes, such as the GMT, TMT or E-ELT, will allow us to test our predictions by searching for truncated WD cooling sequences in globular clusters.

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